

OGLE-2013-BLG-0578L: MICROLENSING BINARY COMPOSED OF A BROWN DWARF AND AN M DWARF

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ABSTRACT

Determining physical parameters of binary microlenses is hampered by the lack of information about the angular Einstein radius due to the difficulty of resolving caustic crossings. In this paper, we present the analysis of the binary microlensing event OGLE-2013-BLG-0578, for which the caustic exit was precisely predicted in advance from real-time analysis, enabling to densely resolve the caustic crossing and to measure the Einstein radius. From the mass measurement of the lens system based on the Einstein radius combined with the additional information about the lens parallax, we identify that the lens is a binary that is composed of a late-type M-dwarf primary and a substellar brown-dwarf companion. The event demonstrates the capability of current real-time microlensing modeling and the usefulness of microlensing in detecting and characterizing faint or dark objects in the Galaxy.

Subject headings: binaries: general, brown dwarfs – gravitational lensing: micro

1. INTRODUCTION

It is known that low-mass stars comprise a significant fraction of stars in the Solar neighborhood and the Galaxy as a whole. The Galaxy may be teeming with even smaller mass brown dwarfs. Therefore, studying the abundance and properties of low-mass stars and brown dwarfs is of fundamental importance. There have been surveys searching for very low-mass (VLM) objects (Reid et al. 2008; Aberasturi et al. 2014), but these surveys are limited to the immediate solar neighborhood. As a result, the sample of VLM objects is small despite their intrinsic numerosity and thus our understanding about VLM objects is poor.

Microlensing surveys detect objects through their gravitational fields rather than their radiation and thus microlensing can provide a powerful probe of VLM objects. However, the weakness of microlensing is that it is difficult to determine the lens mass for general microlensing events. This difficulty arises due to the fact that the time scale of an event, which is the only observable related to the physical lens parameters, results from the combination of the lens mass, distance and the relative lens-source transverse speed. As a result, it is difficult to identify and characterize VLM objects although a significant fraction of lensing events are believed to be produced by these objects.

However, it is possible to uniquely determine the physical lens parameters and thus identify VLM objects for a subset of lensing events produced by lenses composed of two masses. For unique determinations of the physical lens parameters, it is required to simultaneously measure the angular Einstein radius θ_E and the microlens parallax π_E that are related to the

lens mass M and distance to the lens D_L by

$$M_{\text{tot}} = \frac{\theta_E}{\kappa \pi_E}; \quad D_L = \frac{\text{AU}}{\pi_E \theta_E + \pi_S}, \quad (1)$$

respectively (Gould 2000). Here $\kappa = 4G/(c^2 \text{AU})$, $\pi_S = \text{AU}/D_S$ is the parallax of the source star, and D_S is the distance to the source. The angular Einstein radius is estimated by analyzing deviations in lensing light curves caused by the finite size of the lensed source stars (Gould 1994; Nemiroff & Wickramasinghe 1994; Witt & Mao 1994). For a single-lens events, finite-source effects can be detected only for a very small fraction of extremely high-magnification events where the lens-source separation at the peak magnification is equivalent to the source size. On the other hand, light curves of binary-lens events usually result from caustic crossings during which finite-source effects become important and thus the chance to detect finite-source effects and measuring the Einstein radius is high. Furthermore, binary-lens events tend to have longer time scales than single-lens events and this also contributes to the higher chance to measure the lens parallax. In fact, most known VLM lensing objects were identified through the channel of binary-lens events (Hwang et al. 2010; Shin et al. 2012; Choi et al. 2013; Han et al. 2013; Park et al. 2013; Jung et al. 2015).

Despite the usefulness of binary-lens events, the chance to identify VLM objects has been low. One important reason for the low chance is that caustic crossings last for very short periods of time. The duration of a caustic crossing is

$$t_{\text{cc}} = \frac{2\rho}{\sin \phi} t_E, \quad (2)$$

where t_E is the Einstein time scale of the event, ϕ is the entrance angle of the source star with respect to the caustic line, and $\rho = \theta_*/\theta_E$ is the angular source radius θ_* normalized to the angular Einstein radius θ_E . Considering that the Einstein

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time scale is $\sim (\mathcal{O})10$ days and the Einstein radius is $\sim (\mathcal{O})$ milli-arcsec for typical Galactic microlensing events, the duration of a caustic crossing is $\sim (\mathcal{O})$ hours for Galactic bulge source stars with angular stellar radii of $\sim (\mathcal{O}) 1\text{--}10 \mu\text{-arcsec}$. Therefore, it is difficult to densely resolve caustic crossings from surveys that are being carried out with over hourly observational cadences.

Another reason for the low chance of resolving caustic crossings is the difficulty in predicting their occurrence. Caustics produced by a binary lens form a single or multiple sets of closed curves and thus caustic crossings always come in pairs. Although it is difficult to predict the first crossing (caustic entrance) based on the fraction of the light curve before the caustic entrance, the second crossing (caustic exit) is guaranteed after the caustic entrance. To resolve the short-lasting caustic exit, it is required to precisely predict the time of the caustic crossing so that observation can be focused to resolve caustic crossings. This requires vigilant modeling of a lensing event conducted with the progress of the event followed by intensive follow-up observation.

In this paper, we report the discovery of a VLM binary that was detected from the caustic-crossing binary-lens microlensing event OGLE-2013-BLG-0578. The caustic exit of the event was precisely predicted by real-time modeling, enabling dense resolution and complete coverage of the caustic crossing. Combined with the Einstein radius measured from the caustic-crossing part of the light curve and the lens parallax measured from the long-term deviation induced by the Earth’s parallactic motion, we uniquely measure the lens mass and identify that the lens is a VLM binary composed of a low-mass star and a brown dwarf.

2. OBSERVATION

The microlensing event OGLE-2012-BLG-0578 occurred on a star located toward the Galactic Bulge direction. The equatorial coordinates of the lensed star are $(\alpha, \delta)_{J2000} = (17^{\text{h}}59^{\text{m}}59^{\text{s}}.85, -29^{\circ}44'06''.9)$, that correspond to the Galactic coordinates $(l, b) = (0^{\circ}.90, -3^{\circ}.10)$. The event was first noticed on April 22, 2013 from survey observations conducted by the Optical Gravitational Lensing Experiment (OGLE: Udalski 2003) using the 1.3m Warsaw telescope at the Las Campanas Observatory in Chile. Images were taken using primarily in *I*-band filter and some *V*-band images were also taken to constrain the lensed star (source).

In Figure 1, we present the light curve of the event. The light curve shows two distinctive spikes that are characteristic features of a caustic-crossing binary-lens event. The caustic crossings occurred at $\text{HJD}' = \text{HJD} - 2450000 \sim 6426.0$ and 6461.8 . Although the event was first noticed before the caustic crossings, the caustic entrance was missed. With the progress of the event, it became clear that the event was produced by a binary lens from the characteristic “U”-shape trough between the caustic crossings.

Although the first caustic crossing was missed, the second crossing was densely resolved. Resolving the crossing became possible with the prediction of the caustic crossing from vigilant modeling of the light curve followed by intensive follow-up observation. It is known that reliable prediction of the second caustic crossing is difficult based on the light curve before the minimum between the two caustic crossings (Jaroszyński & Mao 2001). With the emergence of the correct model after passing the caustic trough, we focused on the prediction of the exact caustic-crossing time. The first alert of the caustic exit was issued on June 17, 2013, 1.3 days be-

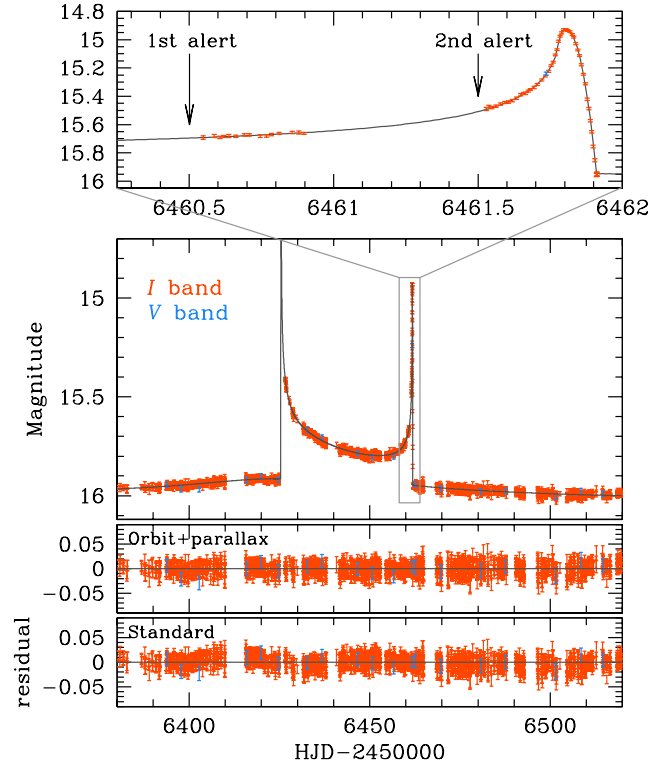


FIG. 1.— Light curve of OGLE-2013-BLG-0578. Also plotted is the best-fit model (“orbit+parallax” model with $u_0 > 0$). The two bottom panels show the residuals from the modeling with and without considering lens-orbital and parallax effects. The upper panel shows the enlargement of the caustic-exit region and the times of caustic-crossing alerts.

fore the actual caustic exit. On the next day, the second alert was issued to predict more refined time of the caustic exit. In response to the alert, the OGLE experiment, which is usually operated in survey mode, entered into “following-up” mode observation by increasing the observation cadence. Thanks to the intensive follow-up observation, the caustic exit was completely and densely covered. See the upper panel of Figure 1.

In order to securely measure the baseline magnitude and detect possible higher-order effects, observation was continued after the caustic exit to the end of the Bulge season. From these observations, we obtain 2284 and 27 images taken in *I* and *V* bands, respectively. Photometry of the event was done by using the customized pipeline (Udalski 2003) that is based on the Difference Imaging Analysis method (Alard & Lupton 1998; Woźniak 2000). We note that the *I*-band data are used for light curve analysis, while the *V*-band data are used for the investigation of the source type.

It is known that photometric errors estimated by an automatic pipeline are often underestimated and thus errors should be readjusted. We readjust error bars by

$$e' = k(e^2 + e_{\min}^2)^{1/2}. \quad (3)$$

Here e_{\min} is a term used to make the cumulative distribution function of χ^2 as a function of lensing magnification becomes linear. This process is needed to ensure that the dispersion of data points is consistent with error bars of the source brightness. The other term k is a scaling factor used to make χ^2 per degree of freedom (dof) becomes unity.

3. ANALYSIS

We analyze the event by searching for the set of lensing parameters (lensing solution) that best describe the observed

light curve. Basic description of a binary-lens event requires seven standard lensing parameters. Three of these parameters describe the source-lens approach including the time of the closest approach of the source to a reference position of the lens, t_0 , the lens-source separation at t_0 in units of the Einstein radius, u_0 , and the time required for the source to cross the Einstein radius, t_E (Einstein time scale). In our analysis, we set the center of the mass of the binary lens as a reference position in the lens plane. Another two parameters describe the binary lens including the projected binary separation in units of the Einstein radius, s (normalized separation), and the mass ratio between the lens components, q . Due to the asymmetry of the gravitational field around the binary lens, it is needed to define the angle between the source trajectory and the binary axis, α (source trajectory angle). The last parameter is the normalized source radius ρ , which is needed to describe the caustic-crossing parts of the light curve that are affected by finite-source effects.

It is often needed to consider higher-order effects in order to precisely describe lensing light curves and this requires to include additional lensing parameters. For long time-scale events, such effects are caused by the positional change of an observer induced by the orbital motion of the Earth around the Sun (“parallax effect”: Gould 1992) and/or the change of the binary separation and orientation caused by the orbital motion of the lens (“lens orbital effect”: Dominik 1998; Albrow et al. 2000). The analyzed event lasted throughout the whole Bulge season and thus these effects can be important. The parallax effect is described by two parameters, $\pi_{E,N}$ and $\pi_{E,E}$, that are the two components of the lens parallax vector π_E projected onto the sky along the north and east equatorial coordinates, respectively. The direction of the lens parallax vector corresponds to the relative lens-source proper motion and its magnitude corresponds to the relative lens-source parallax $\pi_{\text{rel}} = \text{AU}(D_L^{-1} - D_S^{-1})$ scaled to the Einstein radius of the lens, i.e.,

$$\pi_E = \frac{\pi_{\text{rel}}}{\theta_E}. \quad (4)$$

To the first-order approximation, the lens orbital effect is described by two parameters, ds/dt and $d\alpha/dt$, which are the change rates of the normalized binary separation and the source trajectory angle, respectively.

To model caustic-crossing parts of the light curve, it is needed to compute magnifications affected by finite-source effects. To compute finite-source magnifications, we use the numerical method of the inverse ray-shooting technique (Kayser et al. 1986; Schneider & Weiss 1986) in the immediate neighboring region around caustics and the semi-analytic hexadecapole approximation (Pejcha & Heyrovský 2009; Gould 2008) in the outer region surrounding caustics. We consider the effects of the surface brightness variation of the source star. The surface brightness is modeled as

$$S_\lambda \propto 1 - \Gamma_\lambda \left(1 - \frac{3}{2} \cos \psi\right), \quad (5)$$

where Γ_λ is the linear limb-darkening coefficient, λ is the passband, and ψ is the angle between the line of sight toward the source star and the normal to the source surface. We adopt the limb-darkening coefficients $(\Gamma_V, \Gamma_I) = (0.62, 0.45)$ from Claret (2000) based on the source type. The source type is determined based on its de-reddened color and brightness. See Section 4 for details about how the source type is determined.

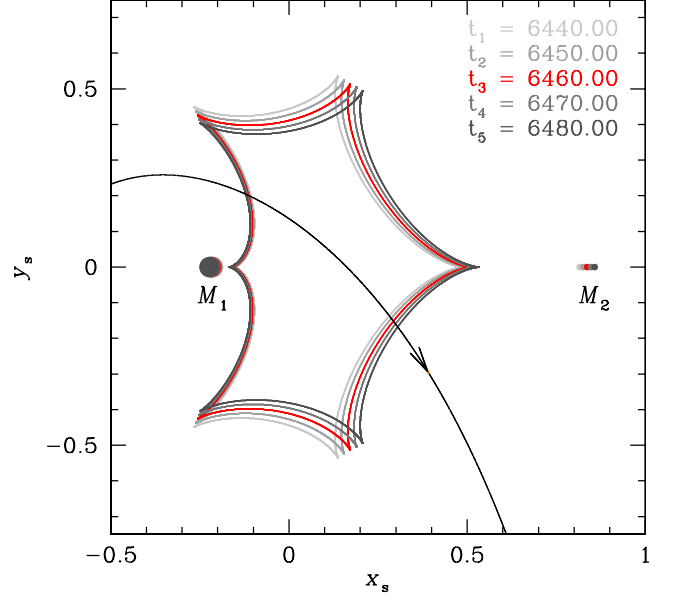


FIG. 2.— The source trajectory (the curve with an arrow) with respect to the caustic (the closed curve with 6 cusps). The two small dots marked by M_1 and M_2 represent the positions of the binary lens components. All lengths are scaled by the angular Einstein radius corresponding to the total mass of the binary lens. Due to the change of the relative positions of the binary lens components caused by the orbital motion, the caustic varies in time. We present 4 caustics and lens positions corresponding to the times marked in right upper corner of the panel. The source trajectory is curved due to the combination of the lens-orbital and parallax effects.

Searching for the best-fit solution of the lensing parameters is carried out based on the combination of grid-search and downhill approaches. We set (s, q, α) as grid parameters because lensing magnifications can vary dramatically with small changes of these parameters. On the other hand, magnifications vary smoothly with changes of the remaining parameters, and thus we search for these parameters by using a downhill approach. We use the Markov Chain Monte Carlo (MCMC) method for the downhill approach. Searching for solutions throughout the grid-parameter spaces is important because it enables one to check the possible existence of degenerate solutions where different combinations of the lensing parameters result in similar light curves.

In the initial search for solutions, we conduct modeling of the light curve based on the 7 basic binary-lensing parameters (“standard model”). From this, it is found that the event was produced by a binary with a projected separation very close to the Einstein radius, i.e. $s \sim 1.0$. Caustics for such a resonant binary form a single big closed curve with 6 cusps. The two spikes of the light curve were produced by the source trajectory passing diagonally through the caustic. See Figure 2 where we present the source trajectory with respect to the caustic⁷. The estimated mass ratio between the binary components is $q \sim 0.2 - 0.3$.

Although the standard model provides a fit that matches the overall pattern of the observed light curve, it is found that there exists some residual in the region around $\text{HJD}' \sim 6410$. See the bottom panel of Figure 1. We, therefore, check whether higher-order effects improve fit. We find that separate consideration of the parallax effect (“parallax model”)

⁷ We note that the source trajectory is curved due to the combination of the lens-orbital and parallax effects. We also note that the caustic varies in time due to the positional change of the binary-lens components caused by the orbital motion.

TABLE 1
LENSING PARAMETERS

Parameter	$u_0 > 0$	$u_0 < 0$
χ^2/dof	2303.1/2300	2328.1/2300
t_0 (HJD)	2456440.13 ± 0.11	2456439.99 ± 0.08
u_0	0.109 ± 0.004	-0.120 ± 0.003
t_E (days)	72.11 ± 0.84	70.79 ± 0.10
s	1.027 ± 0.004	1.035 ± 0.002
q	0.260 ± 0.004	0.241 ± 0.003
α (rad)	0.676 ± 0.007	-0.647 ± 0.007
ρ (10^{-3})	0.96 ± 0.01	0.97 ± 0.01
$\pi_{E,N}$	0.54 ± 0.08	-0.51 ± 0.05
$\pi_{E,E}$	-0.53 ± 0.03	-0.72 ± 0.02
ds/dt (yr^{-1})	0.48 ± 0.14	0.40 ± 0.03
$d\alpha/dt$ (rad yr^{-1})	1.89 ± 0.24	-1.75 ± 0.13

and the lens-orbital effect (“orbital model”) improves fit by $\Delta\chi^2 = 579$ and 344, respectively. When both effects are simultaneously considered (“orbit+parallax model”), the fit improves by $\Delta\chi^2 = 616$, implying that both effects are important. In Figure 3, we present the contours of $\Delta\chi^2$ in the space of the higher-order lensing parameters. Contours marked in different colors represent the regions with $\Delta\chi^2 < 1$ (red), 4 (yellow), 9 (green), 16 (sky blue), 25 (blue), and 36 (purple). It shows that the higher-order effects are clearly detected. Considering the time gap between the caustic crossings that is approximately a month and the long duration of the event that lasted throughout the whole Bulge season, the importance of the higher-order effects is somewhat expected.

It is known that lensing events with higher-order effects are subject to the degeneracy caused by the mirror symmetry of the source trajectory with respect to the binary axis (Skowron et al. 2011). This so-called “ecliptic degeneracy” is important for Galactic Bulge events that occur near the ecliptic plane. The pair of the solutions resulting from this degeneracy have almost identical parameters except $(u_0, \alpha, \pi_{E,N}, d\alpha/dt) \rightarrow -(u_0, \alpha, \pi_{E,N}, d\alpha/dt)$. It is found that $u_0 > 0$ is marginally preferred over the $u_0 < 0$ solution by $\Delta\chi^2 = 25.0$, which corresponds to formally $\sim 5\sigma$ level difference. However, this level of $\Delta\chi^2$ can often occur due to systematics in data and thus one cannot completely rule out the $u_0 < 0$ solution. In Table 1, we present the best-fit parameters of both $u_0 > 0$ and $u_0 < 0$ solutions. We note that the uncertainties of the lensing parameters are estimated based on the distributions of the parameters obtained from the MCMC chain of the solution. We also present the best-fit model light curve ($u_0 > 0$ solution) and the corresponding source trajectory with respect to the lens and caustic in Figures 1 and 2, respectively.

4. PHYSICAL PARAMETERS

By detecting both finite-source and parallax effects, one can measure the angular Einstein radius and the lens parallax, which are the two quantities needed to determine the mass and distance to the lens. The lens parallax is estimated by $\pi_E = (\pi_{E,N}^2 + \pi_{E,E}^2)^{1/2}$ from the parallax parameters determined from light-curve modeling.

In order to estimate the angular Einstein radius, it is needed to convert the measured normalized source radius ρ into θ_E by using the angular radius of the source star, i.e. $\theta_E = \theta_*/\rho$. The angular source radius is estimated based on the de-reddened color $(V-I)_0$ and brightness I_0 of the source star which are calibrated by using the centroid of the Bulge

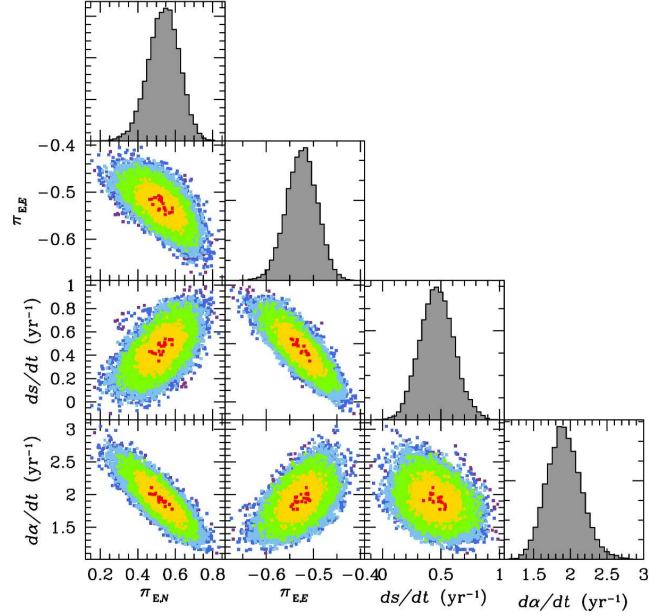


FIG. 3.— Contours of $\Delta\chi^2$ in the space of the parallax and lens-orbital parameters for the best-fit model ($u_0 > 0$ model). Contours marked in different colors represent the regions with $\Delta\chi^2 < 1$ (red), 4 (yellow), 9 (green), 16 (sky blue), 25 (blue), and 36 (purple).

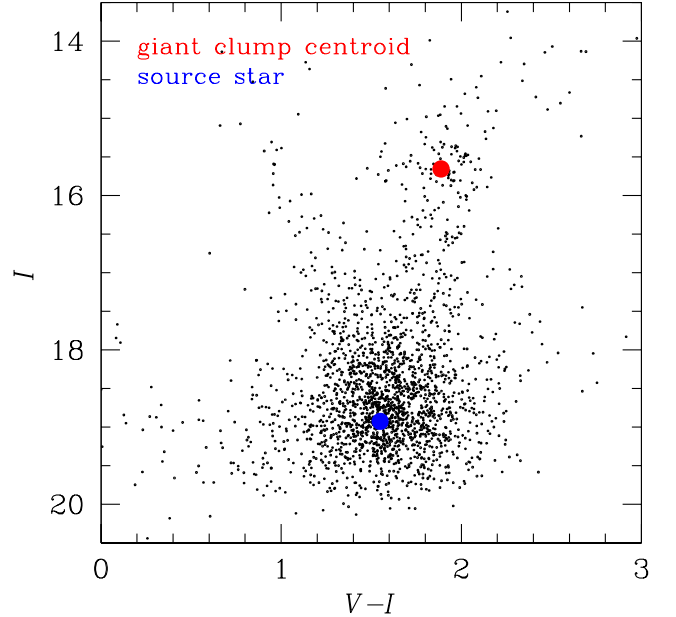


FIG. 4.— Location of the lensed star with respect to the centroid of giant clump in the color-magnitude diagram of neighboring stars.

giant clump on the color-magnitude diagram as a reference (Yoo et al. 2004). By adopting the color and brightness of the clump centroid $(V-I, I)_{0,c} = (1.06, 14.45)$ (Bensby et al. 2011; Nataf et al. 2013), we estimate that $(V-I, I)_0 = (0.72, 17.68)$ for the source star, implying that the source star is a G-type subgiant. Figure 4 shows the locations of the source and the centroid of giant clump in the color-magnitude diagram of stars around the source star. We then translate $V-I$ into $V-K$ using the color-color relation of Bessell & Brett (1988) and obtain the angular source radius by using the relation between $V-K$ and θ_* of Kervella et al. (2004). The determined angular source radius is $\theta_* = 0.93 \pm 0.06 \mu\text{as}$. Then, the Einstein

TABLE 2
PHYSICAL PARAMETERS

Parameter	$u_0 > 0$	$u_0 < 0$
Einstein radius (mas)	0.97 ± 0.07	0.96 ± 0.07
Proper motion (mas yr ⁻¹)	4.90 ± 0.35	4.96 ± 0.35
Total mass (M_\odot)	0.156 ± 0.017	0.133 ± 0.011
Mass of primary (M_\odot)	0.124 ± 0.014	0.107 ± 0.009
Mass of companion (M_\odot)	0.032 ± 0.004	0.026 ± 0.002
Distance (kpc)	1.16 ± 0.11	1.02 ± 0.08
Projected separation (AU)	1.16 ± 0.11	1.02 ± 0.08
(KE/PE) _⊥	0.48 ± 0.20	0.32 ± 0.07

radius is estimated as $\theta_E = 0.97 \pm 0.07$ mas for the best-fit solution ($u_0 > 0$ model). We note that $u_0 < 0$ model results in a similar Einstein radius due to the similarity in the measured values of ρ . Combined with the measured Einstein time scale t_E , the relative lens-source proper motion is estimated as $\mu = \theta_E/t_E = 4.90 \pm 0.35$ mas yr⁻¹.

With the measured lens parallax and Einstein radius, we determine the mass and the distance to the lens using Equation (1). In Table 2, we list the physical parameters of the lens system corresponding to the $u_0 > 0$ and $u_0 < 0$ solutions. We note that the estimated parameters from the two solutions are similar. According to the estimated mass, the lens system is composed of a substellar brown-dwarf companion and a late-type M-dwarf primary. The distance to the lens is $D_L < 1.2$ kpc and thus the lens is located in the Galactic disk. The projected separation between the lens components is $r_\perp = sD_L\theta_E$ is slightly greater than 1 AU. In order to check the validity

of the obtained lensing solution, we compute the projected kinetic to potential energy ratio (KE/PE)_⊥ by

$$\left(\frac{\text{KE}}{\text{PE}}\right)_\perp = \frac{(r_\perp/\text{AU})^2}{8\pi^2(M/M_\odot)} \left[\left(\frac{1}{s} \frac{ds}{dt}\right)^2 + \left(\frac{d\alpha}{dt}\right)^2 \right] \quad (6)$$

(Dong et al. 2009). The estimated ratio is $(\text{KE/PE})_\perp < 1$ for both $u_0 > 0$ and $u_0 < 0$ solutions and thus meets the condition of a bound system.

5. CONCLUSION

We presented the analysis of a caustic-crossing binary-lens microlensing event OGLE-2013-BLG-0578 that led to the discovery of a binary system composed of a substellar brown-dwarf companion and a late-type M-dwarf primary. Identification of the lens became possible due to the prediction of the caustic crossing from vigilant real-time modeling and resolution of the caustic from prompt follow-up observation. The event demonstrates the capability of current real-time modeling and the usefulness of microlensing in detecting and characterizing faint or dark objects in the Galaxy.

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